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TITLE: SIGNAL PERMUTING
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SIGNAL PERMUTING

TECHNICAL FIELD

This invention relates to signal permuting.

BACKGROUND

Signal permuting is used to change the routing paths of signals to connect two interfaces whose sets of signal lines have different orderings. For example, as shown in Figure 1A, if an interface 10 to input circuitry 11 has lines L_0 to L_3 that carry Control, Data 1, Data 2, and Ground signals, and a second interface 12 to output circuitry 13 has lines L_0 to L_3 that carry Data1, Data 2, Ground, and Control signals, the input and output interfaces are coupled by a 4-by-4 permuting network 14 that maps $[L_0, L_1, L_2, L_3]$ to $[L_3, L_0, L_1, L_2]$.

A permuting network can be implemented using switches. In Fig. 1B, the output of an $n:1$ switch 16 can reflect any one of its n inputs. By using a number of $n:1$ switches which receive the same set of n signals at their inputs, n signals can be permuted to any order at their output terminals. Fig. 1C shows a 2-by-2 permuting network implemented using two 2:1 switches 20, 22 that permutes the ordering of two signals S_0 and S_1 .

An $n:1$ switch can be implemented using an $n:1$ multiplexer, a $2^n \times 1$ random access memory that has its contents written to reflect a single address input, or an n -input lookup-table in a field programmable gate array that is programmed to reflect any one of its inputs at its output. For each type of technology, the types of switches that can be most economically implemented may be different.

DESCRIPTION OF DRAWINGS

FIGs 1A-1C are schematic diagrams of switches and permuting networks.

FIGs 2-3 are schematic diagrams of permuting networks.

FIG 4A is a diagram of a mapping between input and output terminals.

5 FIG 4B is a diagram showing transition of position coordinates of signals.

FIG 5A is a schematic diagram of a computer having a permuting network.

FIG 5B is a diagram of a mapping between the input and output terminals of the permuting network of FIG 5A.

FIG 6 is a schematic diagram of a permuting network.

DETAILED DESCRIPTION

10 The invention is directed towards construction of a permuting network using a predetermined set of building blocks. The building blocks are programmable switches of one or more type, each type being able to select one signal from among several signals. The permuting network is configured as a multidimensional switch array permuter (MSAP) that can permute the
15 ordering of signals by programming the switches to select signals according to a permuting algorithm.

In the figures, each permuter has input terminals at its left and output terminals at its right. Referring to Fig. 2, a multidimensional switch array permuter (MSAP) 200 that can permute $N = w_1 \times w_2 \times \dots \times w_D$ signals is implemented using $2D-1$ layers of switches, layers L_1
20 through L_{2D-1} . The numbers w_1, w_2, \dots, w_D are integers. Each layer contains the same number (N) of switches of the same type, but the types of switches may differ among different layers. For $\lambda = 1$ to D , layer L_λ includes $w_\lambda:1$ switches, each of which can select one signal from among w_λ signals. For example, layer L_1 contains $w_1:1$ switches, layer L_2 contains $w_2:1$ switches, and layer

L_D contains $w_D:1$ switches. For $\lambda = D+1$ to $2D-1$, layer L_λ contains $(2D-\lambda):1$ switches. For example, layer L_{D+1} contains $w_{D+1}:1$ switches, and layer L_{2D+1} contains $w_1:1$ switches. By appropriately connecting the output terminals of switches in one layer to the input terminals of switches in the next layer, and appropriately programming the switches to select input signals, MSAP 200 can permute the ordering of a set of signals at its input into any arbitrary ordering of the signals at its output.

The input signals of the switches in layer L_1 are the N input signals of the MSAP. The $w_1:1$ switches in the layer L_1 are configured to form a number of w_1 -by- w_1 permuters 202, the number being N/w_1 . Each w_1 -by- w_1 permuter 202 includes a number of $w_1:1$ switches, the number being w_1 . Each w_1 -by- w_1 permuter 202 receives w_1 signals from the input terminals 204, and outputs a set of re-ordered w_1 signals on the output terminals 206. The output signals 206 of permuters 202 are sent to the input terminals of permuters in layer L_2 . The $w_2:1$ switches in layer L_2 are configured to form a number of w_2 -by- w_2 permuters 208, the number being N/w_2 . Each w_2 -by- w_2 permuter 208 receives w_2 signals at its input terminals 210, and outputs a set of re-ordered w_2 signals at its output terminals 212. The output signals of permuters 208 are sent to the input terminals of permuters in layer L_3 , and so forth.

In general, the switches in layer L_λ ($\lambda = 1$ to D) are grouped into w_λ -by- w_λ permuters, each permuter receiving w_λ signals from the previous layer and generating a set of re-ordered w_λ signals at its output. The switches in layer L_λ ($\lambda = D+1$ to $2D-1$) are grouped into $w_{2D-\lambda}$ -by- $w_{2D-\lambda}$ permuters, each permuter receiving $w_{2D-\lambda}$ signals from the previous layer and generating a set of re-ordered $w_{2D-\lambda}$ signals at its output. The switch outputs in the last layer, L_{2D-1} , are the outputs of the MSAP, which is a set of re-ordered N signals.

The connections between the output terminals of one layer and the input terminals of the next layer are fixed (e.g., hardwired). The connections are represented by the regions 214

enclosed in dashed lines. The connections between each layer are configured so that each of the output signals of a permuter is sent to a different permuter in the next layer. Thus, each w_λ -by- w_λ permuter receives w_λ input signals from w_λ different permeters in the previous layer, permutes the order of the w_λ signals, and sends the re-ordered w_λ signals to w_λ different permeters in the next layer.

An advantage of the invention is that the MSAP can be designed and constructed using various types of switches, depending on which types are available. For example, to design an MSAP that can permute N signals, the factors w_i of N are first determined. Usually the number N can be factored in many ways, each of which corresponds to a different design. For example, suppose the factors w_i are chosen so that $N = w_1 \times w_2 \times \dots \times w_D$, then a MSAP having D dimensions, with w_λ being the width of the λ -th dimension can be designed. The meaning of “width” and “dimension” will be apparent from later descriptions.

For example, there are several MSAP configurations that can permute 48 signals:

- A two-dimensional MSAP can be designed by choosing $N = 48$, $D = 2$, $w_1 = 6$, and $w_2 = 8$. The 48-by-48 MSAP can be built by using a first layer of 6:1 switches, a second layer of 8:1 switches, and a third layer of 6:1 switches.
- A three-dimensional MSAP can be designed by choosing $N = 48$, $D = 3$, $w_1 = 3$, $w_2 = 4$, and $w_3 = 4$. The 48-by-48 MSAP can be built by using a first layer of 3:1 switches, second, third, and fourth layers of 4:1 switches, and a fifth layer of 3:1 switches.
- A five-dimensional MSAP can be designed by choosing $N = 48$, $D = 5$, $w_1 = 2$, $w_2 = 2$, $w_3 = 2$, $w_4 = 2$, and $w_5 = 3$. The 48-by-48 MSAP can be built using first

through fourth layers of 2:1 switches, a fifth layer of 3:1 switches, and sixth through ninth layers of 2:1 switches.

The advantage is apparent when different environments (e.g., different technologies for implementing the switches, or different brands of products of the same technology) provide different types of switches, or allow different types of switches to be implemented most economically. For example, in one environment, the basic building block may be 2:1 switches, and all other $n:1$ switches are constructed from the 2:1 switches. In another environment, the basic building blocks may include both 2:1 and 3:1 switches, and larger switches are built from these two types of switches. An N -by- N MSAP may be constructed using building blocks that are the most economical for that particular environment.

Following the previous example, to permute 48 signals, it is also possible to select a configuration of MSAP in which N is chosen to be larger than 48, so that some MSAP inputs and outputs are left unused. This structure uses more logic circuits, but may allow certain MSAP configurations to be available. For example, by choosing $N = 64$, the following three configurations can be used to construct a 64-by-64 MSAP:

- $N = 64, D = 2, w_1 = 8, w_2 = 8.$
- $N = 64, D = 3, w_1 = 4, w_2 = 4, w_3 = 4.$
- $N = 64, D = 6, w_1 = 2, w_2 = 2, w_3 = 2, w_4 = 2, w_5 = 2, w_6 = 2.$

In general, for a particular environment, if larger switches have to be built from smaller switches, then to permute the same number (N) of signals, a higher dimensional MSAP using smaller switches will use less logic circuitry. In the above example, if the 8:1 and 4:1 switches have to be built from 2:1 switches, then among the three configurations, the six-dimensional MSAP using 2:1 switches is more economical (i.e., will use the smallest number of switches overall). Because the dimensional width w_k is proportional to the sizes of switches, smaller

switches and less logic circuitry can be used by choosing w_1, w_2, \dots, w_D as close together in value as possible. For example, when $N = n^D$, the most economical configuration is to choose $w_1 = w_2 = \dots = w_D = n$. For example, if larger switches have to be constructed from 2:1 switches, then the most efficient design for MSAP is to choose $n = 2$ and use 2:1 switches as the basic building blocks of the MSAP. See Table 1 below for a comparison of the efficiency of MSAP's constructed using switches of various sizes.

In the example shown in Fig. 3A, a 12-by-12 MSAP 300 is constructed from two layers of 3:1 switches and one layer of 4:1 switches. MSAP 300 includes layers L_1 to L_3 . Layer L_1 includes 3:1 switches that are configured to form 3-by-3 permeters 302, 304, 306, and 308. Layer L_2 includes 4:1 switches that are configured to form 4-by-4 permeters 310, 312, and 314. Layer L_3 includes 3:1 switches that are configured to form 3-by-3 permeters 316, 318, 320, and 322. Within each permuter, different switches select different input signals so that there is no overlap in their selections, resulting in a re-ordering of the input signals appearing at the output terminals of the permuter.

Each 3-by-3 permuter in layer L_1 receives 3 signals at its input terminals, permutes the ordering of the 3 signals, and sends the re-ordered 3 signals to three different permeters in layer L_2 . For example, the first output terminal of permuter 302 is connected to the first input terminal of permuter 310. The second output of permuter 302 is connected to the first input of permuter 312. The third output of permuter 302 is connected to the first input of permuter 314, and so forth. In this way, each of the three output signals of a permuter in the layer L_1 will be re-ordered by a different permuter in the layer L_2 .

Likewise, each output of a permuter in the layer L_2 is connected to an input of a different permuter in layer L_3 . Thus, each of the four output signals of a permuter in layer L_2 will be re-ordered by a different permuter in layer L_3 . By properly re-ordering signals using each

permuters, the 12-by-12 MSAP can re-order 12 input signals into any orderings of the 12 output signals.

As an illustration of how permuters re-order signals, dashed lines are shown inside each permuter representing routing of signals from input terminals to output terminals. Twelve input signals with the ordering $[S_1, S_2, \dots, S_{12}]$ are re-ordered into ordering $[S_7, S_5, S_3, S_9, S_8, S_1, S_{10}, S_2, S_6, S_{12}, S_{11}, S_4]$ at the output of MSAP 300. The following illustrates how signal S_3 is re-ordered from line #3 at the input terminal at the left of the figure to line #6 at the output terminal at the right of the figure. Permuter 302 re-orders signal S_3 from input #3 to output #1, which is connected to input #1 of permuter 310. Permuter 310 re-orders signal S_3 from input #1 to output #2, which is connected to input #4 of permuter 318. Permuter 318 then re-orders signal S_3 from input #4 to output #6. The inputs and outputs of the permuters in each layer are numbered #1 to #12 from top to bottom in the figure.

The following describes the connections between the output terminals of switches in one layer and the input terminals of switches in the next layer. These connections are fixed (e.g., hardwired). For description purposes, the switches in each layer of the MSAP are said to form a D -dimensional array. The switches in layer L_λ are denoted as $S[\lambda][x_1, x_2, \dots, x_D]$, with $1 \leq x_k \leq w_k$, k ranging from 1 to D . The number x_1 represents the 1st dimension coordinate of the switch, the number x_2 represents the 2nd dimension coordinate, and so forth. The inputs to these switches will be denoted by adding subscripts to the ends of switch names. For example, switch $S[1][2,3,4]$ has inputs $S[1][2,3,4]_1$, $S[1][2,3,4]_2$, etc. The outputs will be denoted by adding an asterisk (e.g. $S[1][2,3,4]^*$).

The output signals of the MSAP are the outputs of the last layer L_{2D-1} , i.e., the MSAP outputs are $S[2D-1][x_1, x_2, \dots, x_D]^*$ for the various combinations of x_1, x_2, \dots, x_D . To simplify description of notation for the switches, a fictional layer L_0 is used so that the MSAP inputs are

the L_0 outputs. Thus, the MSAP inputs are $S[0][x_1, x_2, \dots, x_D]^*$ for the various combinations of x_1, x_2, \dots, x_D . Although there is no switch $S[0][1, \dots, 1]$, there is a signal $S[0][1, \dots, 1]^*$, which is the MSAP input.

For $\lambda = 1, 2, \dots, D$, the permuters in layer L_λ arbitrarily permute the outputs of the permuters in the previous layer along dimension λ only. This means that the switches in a permuter in layer L_λ only receive signals from switches in the previous layer having labels that are different in dimension λ , and only permute those signals. Each of the $w_\lambda:1$ switches in layer L_λ ($\lambda \leq D$), denoted $S[\lambda][x_1, x_2, \dots, x_D]$, has w_λ inputs, i.e., $S[\lambda][x_1, x_2, \dots, x_D]_1, S[\lambda][x_1, x_2, \dots, x_D]_2, \dots, S[\lambda][x_1, x_2, \dots, x_D]_{(w_\lambda)}$. These inputs map to all the outputs of the previous layer with switch coordinates differing only in dimension λ :

$$\begin{aligned} S[\lambda][x_1, x_2, \dots, x_\lambda, \dots, x_D]_1 &= S[\lambda-1][x_1, x_2, \dots, 1, \dots, x_D]^* \\ S[\lambda][x_1, x_2, \dots, x_\lambda, \dots, x_D]_2 &= S[\lambda-1][x_1, x_2, \dots, 2, \dots, x_D]^* \\ &\dots \\ S[\lambda][x_1, x_2, \dots, x_\lambda, \dots, x_D]_{(w_\lambda)} &= S[\lambda-1][x_1, x_2, \dots, w_\lambda, \dots, x_D]^* \\ (1 \leq \lambda \leq D; \text{ any } x_1, x_2, \dots, x_D) \end{aligned}$$

For $\lambda = D+1, D+2, \dots, 2D-1$, layer L_λ arbitrarily permutes the outputs of the previous layer along dimension $2D-\lambda$ only. This means that the switches in a permuter in layer L_λ only receive signals from switches in the previous layer having labels that are different in dimension $2D-\lambda$, and only permute those signals. Each of the $w_{2D-\lambda}:1$ switches in layer L_λ ($\lambda > D$), denoted $S[\lambda][x_1, x_2, \dots, x_D]$, has $w_{2D-\lambda}$ inputs, i.e., $S[\lambda][x_1, x_2, \dots, x_D]_1, S[\lambda][x_1, x_2, \dots, x_D]_2, \dots, S[\lambda][x_1, x_2, \dots, x_D]_{(w_{2D-\lambda})}$. These inputs map to all the outputs of the previous layer with switch coordinates differing only in dimension $2D-\lambda$:

$$\begin{aligned} S[\lambda][x_1, x_2, \dots, x_{2D-\lambda}, \dots, x_D]_1 &= S[\lambda-1][x_1, x_2, \dots, 1, \dots, x_D]^* \\ S[\lambda][x_1, x_2, \dots, x_{2D-\lambda}, \dots, x_D]_2 &= S[\lambda-1][x_1, x_2, \dots, 2, \dots, x_D]^* \end{aligned}$$

...

$$S[\lambda][x_1, x_2, \dots, x_{2D-\lambda}, \dots, x_D]_{(w_{2D-\lambda})} = S[\lambda-1][x_1, x_2, \dots, w_{2D-\lambda}, \dots, x_D]^*$$

$$(D+1 \square \lambda \square 2D-1; \text{any } x_1, x_2, \dots, x_D)$$

Referring to Fig. 3B, the switches in MSAP 300 have been labeled as $S[\lambda][x_1, x_2], \lambda$

5 ranging from 1 to 3, x_1 ranging from 1 to 3, and x_2 ranging from 1 to 4. For convenience of notation, the MSAP input signals are described as the output signals of layer L_0 , and are labeled as $S[0][i, j]^*$, i ranging from 1 to 3, and j ranging from 1 to 4. Layer L_1 permutes the signals along the first dimension. This means that the switches in layer L_0 , whose outputs are connected to the inputs of a switch in layer L_1 , have labels with different coordinates in the first dimension but same coordinates in the second dimension. For example, the three inputs of switch $S[1][2,3]$ are connected to outputs of switches in layer L_0 as follows:

$$S[1][2,3]_1 = S[0][1,3]^*$$

$$S[1][2,3]_2 = S[0][2,3]^*$$

$$S[1][2,3]_3 = S[0][3,3]^*$$

15 Layer L_2 permutes the signals along the second dimension. This means that the switches in L_1 , whose outputs are connected to the inputs of a switch in L_2 , have labels with different coordinates in the second dimension but same coordinates in the first dimension. For example, switch $S[2][2,3]$ has its four inputs connected as follows:

$$S[2][2,3]_1 = S[1][2,1]^*$$

$$S[2][2,3]_2 = S[1][2,2]^*$$

$$S[2][2,3]_3 = S[1][2,3]^*$$

$$S[2][2,3]_4 = S[1][2,4]^*$$

20 Layer L_3 permutes the signals along the first dimension. For example, switch $S[3][2,3]$ has its three inputs connected as follows:

$$S[3][2,3]_1 = S[2][1,3]^*$$

$$S[3][2,3]_2 = S[2][2,3]^*$$

$$S[3][2,3]_3 = S[2][3,3]^*$$

The output signals of MSAP 300 are the 12 switch outputs from layer L_3 , i.e., $S[3][1,1]^*$ through $S[3][3,4]^*$.

An MSAP switch topology has a recursive structure. If the first and last layers of switches (L_1 and L_{2D-1}) are removed from an MSAP of dimension $D > 1$, the remaining portion is a number of smaller MSAP's of dimension $D-1$, the number being w_1 . In general, in an MSAP with dimension $D > 1$, for each fixed coordinate c between 1 and w_1 in the first dimension, the subset of switches $\{S[\lambda][c, x_2, x_3, \dots, x_D]\}$ (λ ranging from 2 to $2D-2$ and each x_k ranging from 1 to w_k) forms a sub-MSAP of dimension $D-1$ with dimensional widths w_2, w_3, \dots, w_D . Each sub-MSAP has its own sub-MSAP's, and so forth, down to the level of one-dimensional MSAP's. This recursive structure of the MSAP is reflected in the MSAP switching algorithm described below.

The switches in an MSAP are configured according to a switching algorithm so that the MSAP can permute signals in any chosen order. To facilitate description of the algorithm, each input signal to the MSAP is described as having a starting position and a target position. The position of a signal in a particular layer is written as $[x_1, x_2, \dots, x_D]$, and corresponds to the label of the switch that selected the signal as output. For example, in Fig. 3B, the signal at input line #3 has a starting position of $[3,1]$ because the signal is selected by switch $S[0][3,1]$ and reflected at its output. As described previously, layer L_0 is a fictional layer and used just for convenience of description. When the signal propagates to layer L_1 , its position changes to $[1,1]$ because the signal is selected by switch $S[1][1,1]$. When the signal propagates to layer L_2 , its position

changes to [1,2] because the signal is selected by switch $S[2][1,2]$. Then in layer L_3 , the position of the signal changes to [3,2] because the signal is selected by switch $S[3][3,2]$.

In a three dimensional ($D=3$) MSAP, suppose an input signal has a starting position of [2,5,3] and a target position of [4,1,6]. This means that the MSAP switches must be set in a manner so that the input signal $S[0][2,5,3]^*$ is routed to the output signal $S[5][4,1,6]^*$. As a signal propagates through the MSAP, the signal's position is adjusted in each switch layer, reflecting the switches that the signal has propagated through. Because each layer only permutes the signals in one dimension, only one coordinate of the signal's position is adjusted in a layer. For example, in the $D=3$ MSAP, a signal may follow the position path:

$L_0:$ [2,5,3]
 $L_1:$ [8,5,3]
 $L_2:$ [8,7,3]
 $L_3:$ [8,7,6]
 $L_4:$ [8,1,6]
 $L_5:$ [4,1,6]

This position path determines how one switch in each layer must be set. In order that the signal propagates from L_0 position [2,5,3] to L_1 position [8,5,3], switch $S[1][8,5,3]$ must be set to position 2. In order that the signal propagates from L_1 position [8,5,3] to L_2 position [8,7,3], switch $S[2][8,7,3]$ must be set to position 5, and so forth. When all of the position paths for the MSAP's input signals have been determined, all of the switches in the MSAP can be set so that all input signals are routed to the proper output terminals of the MSAP. Thus, a collection of N position paths (or signal paths) can be used to determine a switch-setting configuration for an MSAP.

The MSAP Switching Algorithm

The MSAP switching algorithm provides a way of configuring an MSAP to route input signals to achieve every possible signal permutation at the output terminals. However, the configuration provided by the switching algorithm is not the only way that an MSAP can be configured to permute signals. It is possible to use a “brute-force” method by looking through all possible switching combinations in some intelligent (e.g., recursive) manner to find a solution.

The MSAP switching algorithm includes Algorithm 1, which calls Algorithm 2. In the description of Algorithm 1 below, the MSAP switching procedures are described in terms of signal position paths rather than in terms of MSAP switch settings. There are N signals, each of which has a D -dimensional starting position and a D -dimensional target position. Algorithm 1 determines the position paths for all the signals, giving each signal's position coordinates in each layer from L_0 to L_{2D-1} in a manner that is allowed by the MSAP topology. No two signals can occupy the same position in any layer. The L_0 position of each signal is its starting position. The L_{2D-1} position of each signal generated by Algorithm 1 will match the signal's target position.

Algorithm 1

Algorithm 1 calls itself recursively. Each time Algorithm 1 is called, a parameter Σ that represents a subset of the input signals is passed on to Algorithm 1. When Algorithm 1 is called initially, parameter $\Sigma = \{\text{all the signals}\}$ is passed to Algorithm 1. In subsequent recursive calls, parameter Σ will contain successively smaller subsets of signals. Algorithm 1 keeps track of the depth of its recursion by passing a level parameter λ . When Algorithm 1 is initially called, parameter $\lambda = 1$ is given to the algorithm. When Algorithm 1 calls itself again, parameter $\lambda = 2$ is passed, and so forth.

For any given N, D, w_1, w_2, \dots , and w_D such that $N = w_1 \times w_2 \times \dots \times w_D$, Algorithm 1 performs the steps below using the parameter λ to represent the recursion depth and Σ to represent the subset of signals to operate on. Initially, set $\lambda=1$.

- 5 Step 1: If $\lambda = D$, jump to step 5.
- Step 2: Copy the $L_{\lambda-1}$ position of each signal in Σ to its L_λ position.
- Step 3: Call Algorithm 2 to permute the L_λ positions of signals in Σ , changing only the λ^{th} position coordinate of each signal, in such a way that no two signals in Σ with the same λ^{th} position coordinate have identical $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates.
- 10 Step 4: For each c , ranging from 1 to w_λ , recursively call Algorithm 1, passing parameters:
 Σ = the subset of signals in Σ which have λ^{th} position coordinates equal to c in layer L_λ ; and
 $\lambda = \lambda+1$.
- 15 Step 5: Permute the signals in Σ from their positions in $L_{2D-\lambda-1}$ to new positions in $L_{2D-\lambda}$, by changing the λ^{th} position coordinate of each signal to its λ^{th} target coordinate.

The permutations performed in Steps 3 and 5 of Algorithm 1 permutes signals only along a particular dimension allowable for that layer. For example, the switches in layer L_k permute signals only along dimension k . Algorithm 1 also follows the rule that no two signals occupy the same position in a given layer. This rule can be ensured because Algorithm 2, as described below, moves signals by swapping pairs of signals, thereby preventing collisions of signals (i.e., two signals being selected by the same switch).

Algorithm 2

25 The following is a description of Algorithm 2 called by Step 3 of Algorithm 1. Due to the recursive nature of Algorithm 1, in layer L_λ , all the signals in Σ will have the same 1^{st} to $(\lambda-1)^{\text{st}}$ position coordinates. Their λ^{th} to D^{th} position coordinates, on the other hand, will run through all

possible combinations. Thus, although each signal still has D position coordinates, Σ is effectively a $(D-\lambda+1)$ -dimensional array of signals according to positions in layer L_λ . The λ^{th} position coordinate of each signal in Σ determines the “slice” of this array that signal is in. The $(\lambda+1)^{\text{st}}$ to D^{th} position coordinates of each signal determine the “column” of the array that the signal is in. The definitions of “slice” and “column” are given later. Two signals with the same λ^{th} position coordinates are in the same slice, and two signals with identical $(\lambda+1)^{\text{st}}$ to D^{th} position coordinates are in the same column. Thus, the array of signals in Σ is divided into w_λ different slices, numbered 1 through w_λ . The array is also divided into $w_{\lambda+1} \times w_{\lambda+2} \times \dots \times w_D$ different columns, not numbered. Step 3 of Algorithm 1 only changes the λ^{th} position coordinate of each signal so that a signal only moves within its column.

The following is a description of the terms “slice” and “column.” A slice is a subset of the available position coordinates containing subsets of Σ of signals that are processed by Algorithm 2. For example, consider an MSAP with $D = 5$, $w_1 = 6$, $w_2 = 5$, $w_3 = 4$, $w_4 = 3$, and $w_5 = 2$. In this case, a total of $6 \times 5 \times 4 \times 3 \times 2 = 720$ signals are permuted, each of which has 5-dimensional starting position coordinates and 5-dimensional target position coordinates. For example, the signal starting in one position $[1,1,1,1,1]$ may have a target position $[6,5,4,3,2]$. Suppose Algorithm 2 is called when $\lambda = 3$, representing the 3rd level of recursion in Algorithm 1. In this case, Σ is a subset of signals with constant L_2 position coordinates in dimensions 1 and 2. For example, all the signals in Σ may have L_2 position coordinates of the form $[4,2,_,_,_]$, so that Σ contains exactly $4 \times 3 \times 2 = 24$ signals: $[4,2,1,1,1]$, ..., $[4,2,4,3,2]$.

In Step 2 of Algorithm 1, the L_2 positions of the signals in Σ are copied to their L_3 positions, so the L_3 positions of the 24 signals are also of the form $[4,2,_,_,_]$. Algorithm 2 is called to rearrange the 24 signals in Σ within layer L_3 , i.e., Algorithm 2 changes the L_3 position

coordinates of the 24 signals in Σ . Algorithm 2 divides the 24 signals in Σ into 4 "slices" and 6 "columns" based on their position coordinates. Each of the 4 slices have 6 signals, and each of the 6 columns have 4 signals.

The 4 slices contain those signals with a given 3rd (since $\lambda = 3$) L_3 position coordinate.

There are 4 slices because $\lambda = 3$ and $w_3 = 4$. The slices are called "slice 1" through "slice 4." Slice k contains those signals in Σ whose 3rd L_3 position coordinate is k . For example, slice 3 contains 6 signals whose L_3 position coordinates are [4,2,3,1,1], [4,2,3,1,2], [4,2,3,2,1], [4,2,3,2,2], [4,2,3,3,1], and [4,2,3,3,2]. During this call to Algorithm 2, the signals in slice 3 have these six L_3 positions, although the particular signals occupying those positions may change.

When Algorithm 2 swaps two signals, those two signals will exchange slices, meaning that they will swap their 3rd L_3 -position coordinates. The 6 columns, meanwhile, contain those signals with a given combination of 4th and 5th L_3 position coordinates (the coordinates above $\lambda = 3$). Thus, there is a column whose signals have L_3 position coordinates [4,2,1,1,1], [4,2,2,1,1], [4,2,3,1,1] and [4,2,4,1,1]. There is another column whose signals have L_3 position coordinates [4,2,1,3,2], [4,2,2,3,2], [4,2,3,3,2] and [4,2,4,3,2]. The term "column," as used in this example, describes a set of L_3 position coordinates with their 4th and 5th dimension coordinates fixed. Thus, signals with L_3 position coordinates [4,2,2,3,1] and [4,2,4,3,1] are said to be in the "same column" because their 4th and 5th coordinates [3,1] match. In Algorithm 2, a column always retains the same set of signals after permutation because the swapping action only exchanges two signals in the same column.

Having described the definition of the terms "slice" and "column," the following is a description of the steps performed by Algorithm 2:

1. FOR $S = 1$ TO $w_\lambda - 1$ DO:

2. WHILE slice S contains at least 2 signals with identical $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates
DO:

3. SET X_0 = one of these signals

4. FOR $K = 0, 1, 2, \dots$ DO:

5. Look for a signal Z in slices $S+1$ through w_λ and in the same column as
 X_K (selected in Step 3 or 6) with the following property: Z 's
 $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates are not identical to the $(\lambda+1)^{\text{st}}$ to
 D^{th} target coordinates of *any* signal in slice S . IF found THEN
BREAK from the "FOR K " loop.

6. Select a pair of signals signal Y_{K+1} and X_{K+1} with the following properties:
 Y_{K+1} is in slices $S+1$ through w_λ and in the same column as $X_0, X_1,$
 \dots , or X_K ;
 X_{K+1} is in slice S , and is different from X_0, X_1, \dots , and X_K ;
 Y_{K+1} and X_{K+1} have identical $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates.
There will always be such a pair of signals.

7. END FOR K

8. LOOP:

9. Swap signal Z with signal X_K

10. IF $K = 0$ THEN BREAK from the LOOP

11. SET $Z = Y_K$

12. Z is now in the same column as some X_J . SET K to this J .

13. END LOOP

14. END WHILE

15. END FOR S

Algorithm 2 works by "fixing" one slice at a time, i.e., once a slice is fixed, its signals are not changed in successive calls to the algorithm. The WHILE condition of step 2 checks the current slice for precisely the property that Algorithm 2 is trying to eliminate. When this property is no longer found, that slice is fixed. A fairly small number of times through Steps 3-13 always fixes a slice.

The goal of Steps 3-13 is to move a signal with "duplicate" $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates out of layer S , replacing it with some other signal from above layer S whose $(\lambda+1)^{\text{st}}$

to D^{th} target coordinates are missing from layer S . In the ideal case where these two signals are in the same column, Algorithm 2 just swaps the two signals. However, such a pair of signals may not be in the same column, so a chain of swaps are performed, each of which operates within a different column. The first swap operation moves a signal with missing $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates into layer S , and the last swap operation moves a signal with duplicate $(\lambda+1)^{\text{st}}$ to D^{th} target coordinates out of layer S .

Fig. 4A shows an example of a mapping between the input and output terminals of MSAP 300. Fig. 4B shows an example of how the position coordinates of the input signals of a 12-by-12 MSAP are changed from their starting position coordinates to their target position coordinates. The changes in position coordinates were determined using Algorithm 1 and Algorithm 2 above. Layer L_1 only changes the coordinates of the first dimension, layer L_2 only changes the coordinates of the second dimension, and layer L_3 only changes the coordinates of the first dimension.

An advantage of an MSAP is that it efficiently uses pre-selected switches as basic building blocks. The simplest and most efficient MSAP's use only $n:1$ switches (n being an integer) to permute $N = n^D$ signals. In such a case, there are $2D-1$ layers, each containing N switches. Because $D = \log_n N$, there is a total of $N \times (2 \log_n N - 1)$ $n:1$ switches. Therefore, the amount of logic circuitry required to construct an MSAP using pre-selected switches with fixed switch sizes is on the order of $N \log N$.

A comparison of the efficiency of MSAP's constructed using switches of various sizes is given below in Table 1. Here, it is assumed that larger switches are built from smaller switches. Table 1 shows that an MSAP using larger switch sizes requires more logic circuitry. For example, if 2:1 switches are available, then building an $N=64$ MSAP is the most efficient using eleven 6-dimensional layers of 2:1 switches. Using five 3-dimensional layers of 4:1 switches

requires 36% more logic circuitry. Using three 2-dimensional layers of 8:1 switches requires 91% more logic circuitry. Using one one-dimensional layer of 64:1 switches (effectively a set of parallel multiplexers) requires 473% more logic circuitry.

Table 1

n	$n:1$ switches per layer	Layers	Total $n:1$ switches	2:1 switches comprising each $n:1$ switch ($= n-1$)	Equivalent total 2:1 switches	Ratio vs. $n=2$	Difference vs. $n=2$
2	64	11	704	1	704	100%	0%
4	64	5	320	3	960	136%	36%
8	64	3	192	7	1344	191%	91%
64	64	1	64	63	4032	573%	473%

An application of an MSAP is to permute signals between a motherboard and a daughter board in a computer. Referring to Fig. 5A, a computer 500 includes a daughter board 506 coupled to a motherboard 502 through an interface 504 that has signals lines #1 to #12. The daughter board 506 includes a memory 512 that can be accessed by motherboard 502. Daughter board 506 and motherboard 502 are manufactured by different companies so that motherboard 502 sends signals on the signal lines of interface 504 in an order that is different from the order recognized by memory 512.

Daughter board 506 includes a permuting network 508 that has input terminals connected to interface 504 and output terminals connected to an interface 510, which in turn is connected to memory 512. Permuting network 508 routes the signals in the signal lines of interface 504 to the signal lines of interface 510 with a new ordering that is acceptable to memory 512. The mapping between signal lines of interface 504 and signal lines of interface 510 is shown in Fig. 5B. As an example, the signal s1 on line #1 of interface 504 is mapped to line #7 of interface 510, and signal s12 on line #12 of interface 504 is mapped to line #4 of interface 510. Similarly, the signals sent from memory 512 are re-ordered by permuting network 508 and then passed on to motherboard 502.

Permuting network 508 is implemented using a field programmable logic array (FPGA). The FPGA includes configurable logic components, each of which can be programmed to receive a number of inputs and to pass any one of the inputs to its outputs, just like an $n:1$ switch. When computer 500 is first booted, daughter board 506 communicates with motherboard 502 to determine the required permutation. A processor (not shown) on daughter board 506 executes an MSAP switching algorithm to program the configurable logic components to construct an MSAP that achieves the required permutation.

In the example shown in Fig. 6, a 18-by-18 MSAP 600 is constructed from four layers of 3:1 switches and one layer of 2:1 switches. In this example, $N = 18 = 3 \times 3 \times 2$, $D=3$, $w_1=3$, $w_2=3$, and $w_3=3$. MSAP 600 includes layers L_1 to L_5 . Layers L_1 , L_2 , L_4 , and L_5 include 3:1 switches that are configured to form 3-by-3 permuters. Layer L_3 includes 2:1 switches that are configured to form 2-by-2 permuters. Within each permuter, different switches select different input signals so that there is no overlap in their selections. This results in a re-ordering of the input signals appearing at the output terminals of the permuter.

In Fig. 6, the switch labels are shown inside the permuters. The three switches in a permuter 602 in layer L_1 have the same 2nd and 3rd coordinates but different 1st coordinates. Thus, permuter 602 permutes the position coordinates of input signals in the first dimension. Likewise, other permuters in layer L_1 also permute the position coordinates of input signals in the first dimension. The three switches in a permuter 604 in layer L_2 have the same 1st and 3rd coordinates but different 2nd coordinates. Thus, permuter 604 permutes the position coordinates of input signals in the second dimension. Likewise, other permuters in layer L_2 also permute the position coordinates of input signals in the second dimension.

In a similar manner, permuters in layer L_3 permute the position coordinates of input signals in the third dimension. Permuters in layer L_4 permute the position coordinates of input

signals in the second dimension. Permuters in layer L_5 permute the position coordinates of input signals in the first dimension. Each of the output signals of a permuter in layer L_1 is sent to a different permuter in layer L_2 , each of the output signals of a permuter in layer L_2 is sent to a different permuter in layer L_3 , and so forth.

5 MSAP 600 is designed to allow any of the 18 input signals to be routed to any of the 18 output terminals. In operation, the MSAP switching algorithm is performed to determine the transition paths for the 18 input signals. The transition paths go through the five layers of switches in a way such that each signal is routed to the desired output terminal and that no two signals occupy the same switch. The switches are then programmed to select input signals
10 according to the signal paths determined by the MSAP switching algorithm.

Other embodiments are within the scope of the following claims. For example, the switches may be implemented using devices other than an FPGA. The switches may be programmed by a processor on the motherboard rather than by a processor on the daughter board. The configuration of switches (i.e., which signal is selected from its inputs and reflected
15 at the output) may be dynamically programmable, or be programmable once and then fixed permanently. An MSAP that performs bit permutations can be used as a building block of an encoder/decoder that encrypts/decrypts messages. The MSAP can be used to construct telecommunication networks to route signals from nodes at one location to nodes at another location in a non-blocking manner. The MSAP can also be used in massively parallel or
20 supercomputing applications to route signals among different processors.